Assessment of NASAâ€™s Plans for Post-2002 Earth Observing Missions: Letter Report

Task Group on Assessment of NASA Plans for Post 2000 Earth Observing Missions, Commission on Geosciences, Environment, and Resources, Commission on Physical Sciences, Mathematics, and Applications, National Research Council

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NASA's Plans for Post-2002 Earth Observing Missions

A letter report sent by the Task Group on Assessment of NASA Plans for Post-2000 Earth Observing Missions to Dr. Ghassem Asrar, Associate Administrator for NASA's Office of Earth Science (April 8, 1999).

Task Group on Assessment of NASA Plans for Post 2000 Earth Observing Missions

Board on Atmospheric Sciences and Climate
Commission on Geosciences, Environment, and Resources
Board on Sustainable Development Policy Division
Space Studies Board
Commission on Physical Sciences, Mathematics, and Applications

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NASA's Plans for Post-2002 Earth Observing Missions

April 8, 1999

Dr. Ghassem Asrar
Associate Administrator for Earth Science
NASA Headquarters
300 E Street, SW
Washington, DC 20546

Dear Dr. Asrar:

We are pleased to provide you with the report of the Task Group on Assessment of NASA Plans for Post-2002 Earth Observing Missions. The report was prepared in response to your request for a National Research Council assessment of NASA's candidate mission profile for the period 2003 to 2010 from the perspective of overall scientific priorities, program coherence, and scientific balance.

In conducting this analysis, the NRC drew upon the expertise, members, and past studies of the Board on Atmospheric Sciences and Climate, the Board on Sustainable Development, and the Space Studies Board. The report is based on information provided by your office and representatives of other U.S. Global Change Research Program agencies, review of a number of recent relevant reports from the three boards, and deliberations by members of the task group during and following its meeting on February 10-11, 1999. The task group report, like the candidate mission profile, was developed under a very rapid timetable. Therefore, the report should be viewed as a starting point for a number of actions that are recommended for follow-up rather than as the final word on post-2002 plans.

The Task Group is hopeful that taking the steps outlined in the report will result in Earth science research by NASA, in collaboration with other partners, that is of the highest caliber and is capable of supporting the crucial environmental decisions that face our nation and the world. On behalf of the task group and its related NRC boards, we would be pleased to assist in any way we can.

Sincerely,

Marvin A. Geller, Chair, Task Group on Assessment of NASA Plans for Post 2000 Earth Observing Missions
Eric J. Barron and James R. Mahoney, Co-chairs, Board on Atmospheric Sciences and Climate
Edwin A. Frieman, Chair, Board on Sustainable Development
Claude R. Canizares, Chair, Space Studies Board

NASA's Plans for Post-2002 Earth Observing Missions

I. INTRODUCTION

The Task Group on Assessment of NASA's Plans for Post-2002 Earth Observing Missions (Appendix A) was formed in response to a request from NASA's Office of Earth Science (Appendix B). The Associate Administrator for the Office of Earth Science (OES) requested a fast-track review of NASA's proposed mission scenario (Appendix C) for Earth observing missions during the period from 2003 to 2010. Within the National Research Council (NRC), the study was organized by the Board on Atmospheric Sciences and Climate, the Board on Sustainable Development, and the Space Studies Board, thereby providing a direct link through membership with the NRC units that had published reports with particular relevance to planning for post-2002 Earth observing missions.

Background materials were distributed in advance to the task group; however, given NASA's deadline for completion of work, the task group could meet only once, on February 10-11, 1999. On February 10, the task group held briefings with representatives from NASA; NOAA and the NPOESS (National Polar-orbiting Operational Environmental Satellite System) Integrated Program Office; the U.S. Global Change Research Program; the Office of Management and Budget; and the White House Office of Science and Technology Policy. The task group also held discussions with the chairs of three recent NRC studies pertinent to the current assessment and with several of the authors of the Easton workshop report[1] that evaluated NASA's post-2002 mission scenario (Appendix D shows the meeting agenda and lists all presenters). Task group deliberations began on February 11 and continued informally via e-mail and telephone. According to NASA officials, the rapid timetable for completion of the task group's work was necessary to provide guidance on upcoming budget submissions, technology development efforts for post-2002 missions, and potential negotiations with international partners. The task group notes, and NASA officials acknowledged, the obvious limitations imposed by the rapid timetable for completion of the study. As a result, the task group regards the assessments in this report as preliminary and recommends a number of essential follow-up assessment activities.

The task group's charge (Appendix B) included consideration of the following topics:
1. The extent to which the mission set contributes to a coherent overall program that addresses important science themes and priorities,
2. The responsiveness of the missions to scientific priorities identified in recent relevant NRC reports,
3. Broad aspects of balance between various Earth science discipline areas,
4. General technical and programmatic feasibility,
5. Identification of major scientific or technical problems implicit in the mission scenario, and
6. Evaluation of the efficacy of the process employed by NASA to solicit ideas and to distill them to frame the proposed mission set.

NASA's post-2002 mission plans were an output of the Easton workshop process. As discussed in the report of the workshop, this process began with an RFI (Request for Information). Through the RFI, NASA informed potential respondents of its intention to promote a program of smaller satellite missions with shorter implementation times from inception to launch in order to respond more quickly to new research priorities and to reduce the risk to program objectives from any single mission failure. One hundred responses were received, roughly half from NASA centers. Six disciplinary panels covering complementary domains of Earth system science reviewed the submissions and integrated them into 23 mission concepts. These were analyzed by NASA technical staff and an industrial contractor, and estimated implementation costs were developed.

NASA convened a workshop involving 150 participants in late August 1998 in Easton, Maryland, to review and amend the mission scenario. At the Easton workshop, the responses to the RFI were reviewed by both disciplinary and interdisciplinary panels. Prior to the workshop three categories of NASA Earth-observing missions were defined:

EOS follow-on missions for systematic measurements of critical parameters,

Earth Probe missions for exploratory research or focused process studies, and

Pre-operational instrument development to provide new or more capable sensors for operational observing systems.

The RFI was circulated by NASA to the community with a 6-week response deadline. The Easton workshop was held 10 weeks later, using the RFI responses as a significant input. The report of the Easton workshop was completed approximately 2 months later. To formulate complex program plans on such a short time scale (see Box 1), NASA necessarily built on the very extensive heritage of NRC and NASA studies and reports, as well as 10 years of EOS Science Team operations.

BOX 1
NASA and NRC Milestones Relevant to Post-2002 Mission Planning

NASA RFI Announced	April 10, 1998
NRC *Pathways* Report Overview Volume, with Recommendations and Research Imperatives, Published	May 19, 1998
NRC "NPOESS and Climate Change" Letter Report[2] Published	May 27, 1998
NASA Deadline for Submission of Post-2002 Era EOS Mission Concepts	June 8, 1998
NASA Panel Review of Submissions	Mid-June 1998
NASA Workshop at Easton, Maryland	August 24-26, 1998
Easton Workshop Results Available for Program Formulation	Early September 1998
NRC Report, *The Atmospheric Sciences Entering the Twenty-First Century*, Published	October 22, 1998
Easton Workshop Report ("Kennel Report") Published	November 12, 1998
NRC *Pathways* Full Report Prepublication Release	November 13, 1998

NRC Post-2002 Task Group Meets	February 10-11, 1999
NRC Report, *Adequacy of Climate Observing Systems*, Published	February 26, 1999
NRC Post-2002 Letter Report Target Date for Publication	March 15, 1999

NASA, the USGCRP, and the NRC *Pathways* Report

The task group's evaluation of the process and outcomes of the Easton workshop relies heavily on the recent NRC publication, *Global Environmental Change: Research Pathways for the Next Decade*.[3] This approach is consistent with NASA's intent to rely on Pathways for guidance during the Easton process; it also conforms to the charge for this review. It is important to recognize, however, that the sponsor and audience for the *Pathways* report are broader than NASA. Indeed, *Pathways* provides a comprehensive review and scientific framework for future directions in the U.S. Global Change Research Program (USGCRP). As discussed below, some of what the task group perceives as shortcomings in the Easton process are, in fact, reflections of larger problems within the USGCRP.

The USGCRP was established in 1989 and codified by Congress "to provide for development and coordination of a comprehensive and integrated U.S. research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."[4] This effort requires planning and coordinating research and policy development interests of several U.S. government departments and agencies, including the Executive Offices of the President.[5] Thus, the USGCRP provides a mechanism for obtaining the necessary scientific knowledge to document global change phenomena and enabling informed decision making on potential response strategies. These responses include such international agreements as the Montreal Protocol and the Framework Convention on Climate Change.

The importance of NASA's role in the USGCRP cannot be overstated. For example, NASA's role in understanding the causes of global and polar stratospheric ozone depletion stands as one of the outstanding scientific accomplishments of the last two decades. In addition, the agency's development and implementation of satellite altimetry and scatterometry have made today's approach to global oceanography possible. Overall, NASA accounts for nearly 75 percent of the resources made available under the USGCRP, with some 60 percent devoted to space-based observation programs.[6] Thus, NASA's directions in Earth science during the first part of the next century will be pivotal in determining the success of the USGCRP and in international global change programs such as the World Climate Research Programme, the International Geosphere Biosphere Programme, and the International Human Dimensions of Global Environmental Change Programme.

II. SUMMARY OF KEY FINDINGS AND RECOMMEDATIONS

Although the results of the initial planning phase have merit, the development of a coherent overall EOS program depends on the development of a fully integrated science plan. To ensure a balanced and coherent strategy that will elucidate the key mechanisms thought to underlie global change phenomena, the task group recommends that NASA

develop the science plan with the participation of USGCRP agencies and the academic scientific community and in consultation with international partners.

While the task group believes that NASA's plan for the post-2002 missions tries to be responsive to broad aspects of *Pathways*, the NASA planning effort needs to be refocused on addressing the major unanswered scientific questions specified in *Pathways*.

The task group believes that the results of the Easton workshop gave a mission set that is balanced among the disciplines; however, it has concerns regarding other, more important aspects of balance, especially the balance between space-based and in situ observations. The vital role of research and analysis (R&A) programs in developing an effective program of research must also be acknowledged, and specific plans for linking R&A programs with post-2002 mission plans should be developed.

The task group agrees with NASA that a *successful* transition of certain EOS observations to NPOESS would realize many benefits. It would be premature, however, to place sole reliance on this strategy for key global change time series. The task group also notes that sole reliance on NPOESS for crucial global change science time series would preclude achieving the objectives, noted in *Pathways* and endorsed by NASA, of developing principal investigator-led, technologically agile, missions.

No federal entity is currently the "agent" for climate or longer-term observations and analyses, nor has the "virtual agency" envisioned in the USGCRP succeeded in this function. The task group endorses NASA's call for a high-level process to develop a national policy to ensure that the long-term continuity and quality of key data sets required for global change research are not compromised in the process of merging research and operational data sets.

The task group recommends that NASA establish a broadly based Science Integration Team charged with developing the requirements for data integration and for reviewing NASA's plans for sensor design, data acquisition, and data management to determine if they are consistent with expected scientific uses of the data. This Science Integration Team should build upon the science plan that is to be developed (see first recommendation above).

Constrained by a tight publication deadline and the absence of a detailed post-2002 science plan, the task group was unable to conduct a thorough analysis of the data set characteristics to be acquired (as opposed to the variables to be measured) in NASA's mission scenario.

III. TASK GROUP ASSESSMENTS

1. The extent to which the mission set contributes to a coherent overall program that addresses important science themes and priorities.

NASA has identified five science thematic areas that reflect some of the scientific directions identified in the NRC *Pathways* and *The Atmospheric Sciences Entering the Twenty-First Century*[7] reports, and that draw on the existing EOS science plan.[8] The themes identified by NASA are climate change and variability, the global carbon cycle, the global water cycle, atmospheric composition and ozone, and solid Earth and natural hazards. The proposed mission set tries to address the science priorities in NASA's themes, taking into account the scientific imperatives in *Pathways* and other the recent NRC reports. The experiments proposed will make major contributions to key science and applications problems such as:

- Climate change detection and attribution;
- Marine and terrestrial carbon sources and sinks;
- Seasonal to interannual climate variability;
- Changes to atmospheric ozone;
- Water resources, flood hazards, and severe storm impacts; and
- Ecosystem management, deforestation, and agriculture.

However, embedded in the mission set are issues such as data continuity, instrument calibration and validation, and data simultaneity. The task group could not determine if such issues had been adequately considered.

The proposed mission set has a strong heritage in previous EOS missions, and several important new records will also be initiated, including global precipitation, ocean circulation and terrestrial hydrology (estimated from gravity measurements), and biomass in regrowing forests. These missions have the potential to yield entirely new information on Earth system components. Clearly, however, a more deliberate planning process is needed to identify data gaps and scientific opportunities that remain after this initial planning stage. Plans for continuation of important data records begun in the first series of EOS missions need a rigorous assessment to ensure that the strategy will meet long-term continuity requirements for Earth science. Quite possibly, major changes in the mission plans will be needed as a consequence of this next stage of planning. Furthermore, new measurements of immense scientific value may be possible in the coming decade, including, for example, additional tropospheric species, three-dimensional winds, and CO_2 vertical profiles. These and other opportunities would complement the existing program.

The development of a coherent overall EOS program depends on the development of a fully integrated science plan. This plan must identify or address:

1. Instrument synergism (i.e., which experiments should overlap in the same time period);
2. NASA's contributions to the major scientific questions and priorities outlined by *Pathways* and other recent NRC reports (those listed in Box 1);
3. The interagency partnerships and collaborations necessary to address these issues and priorities, including the balance between in situ and satellite-based measurements;
4. The role of international partners;
5. An assessment of the overall characteristics of the data sets and their suitability for addressing key scientific questions and priorities;
6. Data management;
7. The role of field studies, data assimilation, and modeling studies;
8. Balance and integration of long-term, consistent observations and exploratory efforts; and
9. Potential uses of observations and data in applications.

This science plan is crucial for mission planning and for gaining strong support from the Earth sciences community. NASA expects to complete its science plan for the post-2002 missions by September 1999.[9] The integration of the missions into a consistent set has to be addressed in the science plan, which then would also set conditions for the time line of the missions, data management, and modeling. Timing will be crucial for those missions where achieving maximum science benefit requires that observations from different missions be combined.

The task group expects the science plan to draw from the EOS science plan, address the detailed recommendations given in *Pathways* and other recent NRC reports, and take note of Decision 14 at the COP4 of UNFCCC in Buenos Aires.[10] The task group recommends that the science plan to underpin the mission set be developed in an open and deliberative process involving the full range of scientific disciplines and a diverse set of potential users. **To ensure a balanced and coherent strategy that will elucidate the key mechanisms thought to underlie global change phenomena, the task group recommends that NASA develop the science plan with the participation of USGCRP agencies and the academic scientific community and in consultation with international partners.** In addition to experts in the various disciplines, NASA should involve scientists who understand the human role and the socioeconomic and health impacts of the designated priority science and applications problems.

Certainly, a very significant part of the science plan should address how the individual mission data streams will be merged and how modeling and assimilation systems will be applied. NASA's observation strategy must be tied to a data management strategy if the scientific goals of the EOS program are to be achieved. NASA's plan to rely on its Federation concept for data production and management coupled with the planned change toward greater emphasis on a PI (principal investigator) mode of operation raises a number of issues related to how a long-term data record, and concurrent calibration and instrument performance metadata, will be guaranteed. While this letter report focuses on the transition to the "NPOESS era," the problem of how to ensure data continuity is broader and includes, for example, the issue of how to introduce innovations into the data management system while maintaining continuous records.

2. The responsiveness of the missions to scientific priorities identified in recent relevant NRC reports.

The task group reviewed NASA's plan for post-2002 missions based on provided text material, presentations by NASA and NPOESS personnel, and with reference to the recent NRC reports noted below, especially the *Pathways* report:

- "On Climate Change Research Measurements from NPOESS," letter, May 1998;
- *The Atmospheric Sciences Entering the Twenty-First Century*, October 1998;
- *Global Environmental Change: Research Pathways for the Next Decade*, prepublication copy, November 1999 (the Pathways report); and
- *Adequacy of Climate Observing Systems*, February 1999.

The authors of NASA's *Report of the Workshop on NASA Earth Science Enterprise Post-2002 Missions* (the Easton workshop report, also known as the Kennel report) found "the 1995 La Jolla review and this 1998 [RFI to Easton] process and workshop responsive to the National Academy of Sciences' *Pathways* report" (p. 25). Indeed, the task group concurs that the RFI and the outcome of the Easton workshop were consistent with important elements of Pathways. Specifically, the RFI notified respondents of NASA's intent to promote a program of smaller satellite missions with a shorter implementation time; NASA has stated that post-2002 mission development and selection will be science-driven; NASA intends to emphasize PI-led missions in its post-2002 planning; post-2002 mission scenarios have a "systematic" measurement component for acquisition of long time series; and NASA has several programs to infuse new technology into Earth observation programs.

However, the task group finds that there is much more work to be done for NASA to be responsive to the full set of standards set by the *Pathways* report, both in planning and in *implementing* the *Pathways* recommendations. For example, the *Pathways* report advocates a USGCRP scientific strategy-including supporting observational, data management, and analysis activities-that is:
1. Agile-to enable timely response to technological changes or to changing research priorities;
2. Focused-to enable progress on answering specific, central scientific questions about global change phenomena; and

3. Coherent-to enable a balanced (e.g., space-based and in situ) and integrated, interagency response to global change issues.

The task group believes that the Easton process mostly addresses only the first element above (via its call for "agility, responsiveness and a PI mode of operation"). Deficiencies in the latter two elements can be traced to the rapidity of the Easton process, the absence of a completed science plan, and the need for further integration with the USGCRP. Although the full *Pathways* report, with detailed information on research and observations in each thematic area, was not available at the time of the Easton workshop, the published Overview volume presented the full set of Scientific Questions from which it should have been possible to elaborate a "focused" and "coherent" effort.

The task group believes that the Easton process was hampered by its abbreviated timetable. NASA intended its solicitation to reach the broad scientific community; the task group fully supports this strategy. However, the rapidity of the process-especially the initial 6-week phase-may not have facilitated the desired response. The task group notes that fully 50 percent of the RFI responses were from NASA centers. Nevertheless, it also notes that some very exciting proposals emerged from the RFI. With careful structure, an earlier announcement, and a longer period for community response to the RFI, an improved solicitation and planning cycle should be achievable within an approximately 1-year period and is recommended for the future.
The *Pathways* report outlines a research framework across the wide scope of global environmental changes in terms of the following primary topical areas:

- Changes in the Biology and Biogeochemistry of Ecosystems,
- Change in the Climate System on Seasonal to Interannual Timescales (S-I),
- Changes in the Climate System on Decadal to Century Timescales (Dec-Cen),
- Changes in the Chemistry of the Atmosphere,
- Paleoclimate, and
- Human Dimensions of Global Environmental Change.

The discussion of each of these six primary topical areas is structured in terms of Research Imperatives-central issues posed to the corresponding scientific community by the challenge of global environmental change. Each research imperative is addressed by a set of Scientific Questions posed at a level of detail from which an observational program, space-based and in situ, can be defined, refined, and realized.

The NASA themes do not directly correspond to the *Pathways* themes, and the specific questions discussed in *Pathways* were not the basis of a rigorous evaluation of the proposed missions during the Easton process. More importantly, *Pathways* calls for an integrated and balanced program of in situ and space-based measurements together with modeling, theory, and process studies. Noting the USGCRP's central contributions to science-driven programs, *Pathways* also includes recommendations related to enhancing the research and analysis (R&A) component of a restructured national strategy for Earth observations.[11]

The Easton process was a NASA-sponsored exercise that could not address some of these important issues and did not address others. In fact, the creation of a fully integrated program, as called for in *Pathways*, represents a major challenge to all of the USGCRP agencies and their scientific partners. Perhaps the most serious deficiency in NASA's post-2002 mission scenario relates to missions intended to support research on long-term processes in the Earth system. The global change program is fundamentally a research program on how Earth may change in the future on time scales of years to decades and longer. Historically, NASA has seen its role as an agent to develop research instrumentation that can become operational to permit agencies such as NOAA to perform such "monitoring" missions. This sets up a fundamental conflict with *Pathways*.

The research challenges in Dec-Cen, S-I, Ecosystems, and Atmospheric Chemical Change require measurements on the time scale of the relevant processes and long-term consistency. This may require observations over several ENSO (El Niño, Southern Oscillation) cycles, over the disturbance and regrowth cycle in forests, over an extended period to examine changes in the ice caps, or over the time period for the stratosphere to evolve as ozone-depleting compounds decay. These are central science questions for global change research in frontier areas, but it is not at all clear that they can be readily transferred to operational settings without diminished standards for calibration, stability, and continuity.

Nor is it clear that researchers are yet making the correct measurements. There must be room allowed for mission concepts that preserve continuity for time series while enhancing the quality of the measurement or greatly reducing its cost through technological improvement. Interagency collaboration is essential, and there must be a rigorous process for transferring responsibilities to operational missions-one that also ensures the continuity of measurements required to address critical questions whose answer is not amenable to this mode of operation. Indeed the distinction between long-term science (the study of processes that occur on long time scales) and monitoring (the routine observation of processes for operational forecasting, early warnings, or management) must be made crystal clear.

The task group concurred with the conclusion of the Easton report that when considering NASA's new approach to mission planning and implementation, "the single most critical concern is the lack of a national policy to address long-term measurements to meet known national and international needs" (p. 26). The task group was made aware of NASA's call for a high-level process to develop a national policy to ensure that the long-term continuity and quality of key data sets required for global change research are not compromised in the process of merging research and operational data sets.12 Such a process is needed to address the task group's concerns regarding continuity and integrity of certain long-term measurements. Neither NASA nor any other single agency can develop such a policy on its own; it will necessarily involve examination of the missions and responsibilities of a number of federal agencies. The task group believes that a strategy of migration to NPOESS simply on the grounds of the length of measurement time is both ill-advised and in conflict with the recommendations in the *Pathways* report. Indeed, as discussed in item 5 below, the task group believes that far greater effort in leadership and planning is necessary to ensure continuity in the transition of research to operations.

3. Broad aspects of balance between various Earth science discipline areas.

The need for discipline balance derives from the fact that many important problems in the Earth sciences involve an interplay among individual disciplines. A familiar example is understanding ENSO phenomena. ENSO involves a joint oscillation of the atmosphere and ocean; therefore, any sensible study approach must include observation and modeling of both the atmosphere and ocean. It is becoming increasingly clear that many, if not most, Earth science problems require an interdisciplinary approach for their understanding and prediction. Currently, some of the most interesting scientific problems occur at disciplinary interfaces.

There also needs to be a balanced approach to assessing and integrating the diverse observations in NASA's suggested mission set. A data system is required that facilitates the merging of diverse data sets for interdisciplinary science. There needs to be a balance between mission measurement, modeling, and data analysis activities for the solution of problems. Without such balance, progress will not be possible on many of the cross-cutting scientific themes. There should also be a balance between research and applications in the design of programs. Some of the same data streams will be used for both scientific research and societal applications.

For example, climate information on storm frequency is used to validate the output of climate models, but it is also useful for assessing logical rate structures for the insurance industry. Similarly, data on the productivity of marine and terrestrial systems, which is critical for improving our understanding of the carbon cycle, can also be used in developing early warning systems for conditions likely to give rise to public health problems, for example, cholera and famine. Without a balance between research and applications, realization of potential benefits such as these will not be possible.

There also needs to be a balance between conservatism and innovation. Conservatism is needed to give confidence that a long-term data set will be acquired, but innovation is needed to design new observational systems that will obtain previously unavailable data, obtain data that may have higher quality or accuracy, and/or acquire data at less cost in the future. **The task group believes that the results of the Easton workshop gave a mission set that is balanced among the disciplines; however, it has concerns regarding other, more important aspects of balance, especially the balance between space-based and in situ observations.** Another critical aspect of achieving program balance is the role of research and analysis programs. **The vital role of research and analysis (R&A) programs in developing an effective program of research must also be acknowledged, and specific plans for linking R&A programs with post-2002 mission plans should be developed (see Box 2).**

BOX 2

Supporting Research and Data Analysis in NASA's Science Programs

Principles for Strategic Planning

Finding: The [R&A] task group finds that R&DA is not always thoroughly and explicitly integrated into the NASA enterprise strategic plans and that not all decisions about the direction of R&DA are made with a view toward achieving the goals of the strategies. The task group examined the trend and balance of R&DA budgets and found alarming results; it questions whether these results are what NASA intends.

Recommendation 1: The task group recommends that each science program office at NASA do the following:

- Regularly evaluate the impact of R&DA on progress toward the goals of the strategic plans.

- Link NASA research announcements (NRAs) to addressing key scientific questions that can be related to the goals of these strategic plans.

- Regularly evaluate the balance between the funding allocations for flight programs and the R&DA required to support those programs (e.g., assess whether the current program can support R&DA for the International Space Station).

- Regularly evaluate the balance among various subelements of the R&DA program (e.g., theoretical investigations; new instrument development; exploratory or supporting ground-based and suborbital research; interpretation of data from individual or multiple space missions; management of data; support of U.S. investigators who participate in international missions; and education, outreach, and public information).

- Use broadly based, independent scientific peer review panels to define suitable metrics and review the agency's internal evaluations of balance.
- Examine ways to maximize familiarity with contemporary advances and directions in science and technology in the process of managing R&DA, for example, via the appropriate use of rotators.

Source: Excerpted from National Research Council, Space Studies Board *Supporting Research and Data Analysis in NASA's Science Programs: Engines for Innovation and Synthesis*, National Academy Press, Washington, D.C., 1998, pp. 63-64.

4. General technical and programmatic feasibility.

The first objective of NASA's Earth Science Enterprise (ESE)[13] is "to fulfill its commitment to the science community, to maintain continuity of key EOS measurements, and deliver consistent time series of global observation over the period of time required by the nature of the Earth system."[14] The task group endorses this priority. However, in executing the ESE mission scenario, NASA assumes integration of its global observation program with the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program. Though NASA, NOAA, and DOD are working in good faith to accomplish such a convergence, it is far from clear that such a convergence will occur, or how well a converged tri-agency program will serve diverse user communities.

Moreover, it is far from certain whether scientific innovation, continuous improvement of measurement capabilities, a PI mode of operation, and technological agility can be pursued within the constraints of convergence, even given the best scenario for management and oversight. Thus, these program attributes, which both NASA and the task group endorse, might be missing from measurement programs addressing some of the most critical global change science issues. Prior to any convergence of EOS and NPOESS missions, NASA and NOAA anticipate a series of "bridging missions" (see ESE Missions EOS-2, EOS-3, and EOS-4 in the Easton workshop report). Successful accomplishment of these is an important first test of the convergence approach. It is also important to emphasize NASA's strength in developing new technology for the Earth observation community. *Pathways* Overview Recommendation 4 emphasizes the importance of technological innovation in "the restructured national strategy for Earth observations" (p. 30). However, the task group was not presented much detail from NASA on how technological innovation can be brought to bear on the entire set of future missions.
The NASA strategy for long time-series measurements depends on effective partnerships with the operational agencies as well as international partners to ensure the delivery of critical Earth science data sets. In regard to the NPOESS missions, NASA has not been an active partner beyond the provision of new technology. The task group is also concerned that innovative measurements and techniques developed by NASA will not be continued under NPOESS, largely as a result of cost considerations.

The task group recognizes that NASA plans to become a more active partner with NPOESS; this is evidenced by NASA's plans to participate in the proposed "bridging" missions. However, the approaches of the operational agencies and NASA to acquiring critical data sets are fundamentally different, and NASA's research-driven requirements require considerably more insight into the design and technical implementation of the observing system. If NASA is to rely on operational observing systems, then it must play an active role in the process from beginning to end. Similarly, international partnerships will continue to play an important role in NASA's strategy. Rapid redesigns and shifts in strategy are generally not conducive to the formation and maintenance of such partnerships, which require years of sustained involvement from all parties.[15]

In summary, the task group notes that **no federal entity is currently the "agent" for climate or longer-term observations and analyses,[16] nor has the "virtual agency" envisioned in the USGCRP succeeded in this function.** Similarly, the authors of the Easton workshop report concluded that "the single most critical concern [with the new NASA approach toward post-2002 missions] is the lack of a national policy to address long-term measurements to meet known national and international needs" (p. 26).[17] **The task group endorses NASA's call for a high-level process to develop a national policy to ensure that the long-term continuity and quality of key data sets required for global change research are not compromised in the process of merging research and operational data sets.** It also concurs with NASA that "the Nation lacks a strategy for ensuring the availability of long-term, well-calibrated satellite observations."[18]

5. Identification of major scientific or technical problems implicit in the mission scenario.

Emerging science issues focus increasingly on specific research questions about interactive Earth system processes whose study requires multiple data types. NASA has recommitted itself to an integrated program of systematic observations and process studies where science questions drive technology development and implementation. However, a strategy for coordinating sensor deployments, data acquisition, and data management is needed to optimize the multiple uses of these data.

Explicit coordination plans are needed to provide multidisciplinary data for research that requires integration of data from more than one sensor. Potential deployment plans need to be fully reviewed by the relevant scientific communities, with sufficient opportunities to provide advice on adjusting sensor design, data acquisition plans, and data archiving plans. For example, having the opportunity to consider mission trade-offs would provide more effective use of NASA data by broader parts of the scientific user community.

NASA has developed several programs (e.g., Instrument Incubator Program, New Millennium Program, Earth System Science Pathfinders) designed to infuse new sensor technologies into the post-2002 EOS program. However, as noted elsewhere in this letter report, the Easton mission set is conservative in its application of new technologies and alternative mission architectures. A more deliberate planning process might lead to more innovative approaches.

The task group endorses the PI model that NASA has adopted for new sensor development, originating from the scientific community, as the basis for instrument development. This is a significant part of NASA's plan to ensure that the science objectives are the focus of new sensor missions. In addition, given the emerging science strategy of having a number of distinct PI-led missions, **the task group recommends that NASA establish a broadly based Science Integration Team charged with developing the requirements for data integration and for reviewing NASA's plans for sensor design, data acquisition, and data management to determine if they are consistent with expected scientific uses of the data.** The broadest use of NASA sensor data, and support for the NASA systems, will be facilitated by including interagency and international investigators on the team. Additionally, including other stakeholders in the Science Integration Team will allow early discussions of joint missions and leveraging of other space research programs. Timely advice on the progress of sensor programs and on the use and integration of the data could be achieved by having the NASA mission scenarios and sensor plans reviewed externally at approximately 3-year intervals.

Support within the scientific community for the EOS program requires a workable plan for distributed data management that provides easy access to data by a wide range of investigators.

The task group encourages the continued development of NASA's Federation concept for data archiving and distribution.[19] While this model provides a good method to ensure linkage to data quality control, calibration, validation, and data continuity, it also raises concerns about whether data will be widely available to support data fusion and integration activities. The design and execution of a data system that satisfies the diverse Earth science and applications communities, yet does not expand to the point that it "squeezes out" the necessary resources for the science and applications that it is meant to enable, is both a necessary and difficult task that lies ahead for NASA.

Long-term climate data records require an integrated, consistent program for sensor calibration, cross-sensor calibration, and data product validation. NASA has demonstrated expertise in pre-launch sensor calibration, cross-sensor calibration, and post-launch vicarious sensor calibration methods and should continue to provide this service as a unique NASA contribution under a joint interagency commitment to NPOESS. In addition, NASA has established a history of successfully organizing field validation experiments (e.g., in the area of land cover/land use, HAPEX, BOREAS, LBA)[20] that demonstrate the contribution of this type of program to Earth science research.

However, constrained by a tight publication deadline and the absence of a detailed post-2002 science plan, the task group was unable to conduct a thorough analysis of the data set characteristics to be acquired (as opposed to the variables to be measured) in NASA's mission scenario (see Box 3). Similarly, many critical data sets that are planned by NPOESS represent a continuation of today's measurements, rather than the enhanced measurements developed by the Earth science community for flight on the EOS missions. A rigorous assessment is necessary to determine if the "continued" data will be adequate for the needs of the scientific community. An example is shown in Box 4.

BOX 3

Challenges in Evaluating the Easton Mission Scenario

The task group's difficulties in evaluating the Easton mission scenario are illustrated with the following example. For studies of climate variability, the two highest-priority measurements related to global ocean circulation are ocean topography and ocean winds. The present NASA strategy for ocean topography has a multiyear gap between the joint NASA/CNES Jason-1 mission with transition to an altimeter mission of uncertain quality on NPOESS. Given the time scales of variability in ocean circulation, the task group views this as a serious deficiency.

For ocean winds, NASA is relying on a transition from QuikScat to SeaWinds to ASCAT (on ESA missions). The research community has identified satellite coverage as a critical component of an effective strategy to observe ocean winds, and there are risks that the reliance on a single scatterometer (ASCAT) will prove inadequate to resolve critical processes for climate variability.

Aside from the likely gap in ocean topography data between Jason-1, the follow-on to TOPEX/Poseidon that is planned for operation through 2006, and the Ocean Altimeter, which may begin operation when NPOESS is launched in approximately 2009, there remain concerns related to data quality for both ocean topography and ocean winds. The task group could not evaluate these risks, but instead highlights them as representative of a broader class of issues that must be addressed. For science issues that rely on long-term, systematic observations it is essential that the characteristics of the data sets be evaluated in a careful and thorough manner, not simply by the presence or absence of a critical measurement. Such an analysis was not completed at the Easton workshop.

BOX 4

Continuity of EOS Measurements

Ocean color is used to estimate concentrations of phytoplankton in the upper ocean. In a similar manner, satellite measurements of visible radiance are used to estimate characteristics of terrestrial vegetation for both monitoring and process studies. Marine and terrestrial vegetation measurements from space will play a critical role in the proposed Carbon Cycle Science program of the USGCRP. Currently, the NPOESS plan for long-term continuity of these data sets is to have instruments provide data with nearly identical characteristics as that provided by present-day sensors such as SeaWiFS and AVHRR.

While continuation of the data sets is valuable, sensors planned for EOS (MODIS and ASTER) are significantly more capable in terms of spectral and spatial resolution as well as sensor performance. For example, these sensors will greatly improve our estimates of ocean primary productivity (through the use of the chlorophyll fluorescence bands on MODIS) and land cover processes (through the use of the 250-meter-spatial-resolution bands). Thus the NPOESS plans represent a step backwards in capability.

Inaccurate or insufficiently sampled measurements often lead to erroneous conclusions; they always result in large uncertainties. The task group could easily identify gaps in plans for acquisition of necessary data. Somewhat more difficult was identifying inefficient measurement strategies, in which a minimally complete set of scientifically related measurements might not be acquired simultaneously, thus resulting in an overall data set with far less scientific potential than would appear from measurement summaries.

Inaccurate or insufficiently sampled measurements are even harder to identify from program summaries in which instruments, missions, and data are examined in relative isolation from the specific science problems to be addressed. The task group emphasizes that its review did not, and could not, address these latter issues, yet they are critical given the need for continuous high-quality data, the size of the national investment being discussed, and the need for the overall national program to rapidly demonstrate scientific progress and to develop a strong foundation of knowledge on which policy makers can depend.

6. Evaluation of the efficacy of the process employed by NASA to solicit ideas and to distill them to frame the proposed mission set.

The task group addresses this question above in this report, especially in the response to the second topic in the charge.

IV. THE FUTURE

In *Pathways*, the National Research Council recommends that NASA's EOS program be restructured and focused on critical scientific issues and unresolved questions about global environmental change that are fundamental to scientific understanding and policy. While providing a framework for a sharply focused scientific strategy and a coherent programmatic structure, the *Pathways* report did not attempt to elaborate a plan for its implementation. Indeed, the next step identified in the report is development of a detailed science implementation plan. This will require reviewing and mapping the USGCRP activities against the set of Research Imperatives and unanswered Scientific Questions presented in the *Pathways* report to help set optimal programmatic priorities, as well as considering implications for the research strategy from new policy developments. The detail provided in the full *Pathways* report that was unavailable at the time of the Easton workshop should be helpful in guiding development of science-driven Earth observation missions.

The task group endorses NASA's stated intent to make the ESE science-driven and toward that end recommends that NASA, working with its USGCRP partners, build on the Easton process with a new round of planning to begin immediately. As noted above, there would be many benefits in pursuing a more deliberate approach in this planning cycle. Consistent with the *Pathways* report, and with NASA's stated intention, the process should begin by utilizing the scientific community's consensus on the fundamental questions in Earth system science. The optimal mix of ground-, aircraft-, balloon-, and space-based measurements to address these questions should then be developed. While execution of the resultant program will necessarily involve all of the USGCRP agencies, NASA's role is key. The task group also recommends that in developing the observing program, the critical roles of theory, laboratory work, field programs, computer modeling, and data analysis should also be fully considered.[21]

The planning process should be an orderly one that is aimed at minimizing the continual changes that have been the hallmark of the EOS program. To do this, the task group believes that the Earth science community must be closely involved from the outset in the NASA planning, and that this process should be viewed as an iterative procedure with regular external reviews. The process also must include more attention to intricate issues associated with reaching consensus and then ensuring the continuity of key long time-series measurements. The current strategy of hand-off to NPOESS is budget-driven. If the strategy is to be successful, a multitude of technical, budgetary, and organizational issues must be resolved.[22] Even in the best case, the science supported by the converged system will have less ability, compared with other science areas, to rapidly advance measurement capabilities, deploy "agile" new missions, or operate in a science-driven PI mode.

Ensuring continuity of operational data, evaluating the readiness of a given "research" data series to move to an operational status, and managing the "research-to-operations" transition of data are problems that will require scientific community involvement and NASA leadership among the USGCRP agencies. Near-term plans must be developed to continue such valuable measurements as ozone, precipitation, scatterometry, and altimetry. The task group also notes that NPOESS instruments are proposed to continue most, but not all, of the ocean color measurements on SeaWiFS (Sea-viewing Wide Field of view Sensor), and they continue the NDVI (Normalized Difference Vegetation Index) measurements now provided by the AVHRR (Advanced Very High Resolution Radiometer) instrument on the NOAA Polar-orbiting Operational Environmental Satellites (POES). As noted above, for all of these variables, a rigorous assessment is necessary to determine if the "continued" data will be adequate for the needs of the scientific community. Longer-term plans must allow for integration of potential follow-ons to NASA's EOS AM-1, PM-1, and CHEM, preparations for possible NASA-NOAA bridge missions, and the possible transition of some measurements to NPOESS starting in approximately 2009.

It is abundantly clear that NASA's ESE program cannot, and should not, be carried out in isolation from the rest of the USGCRP (nor from international partners). While not the subject of this report, it is also clear that the USGCRP would benefit from closer coordination of its agency components, the most important of which is NASA. As stated in the *Pathways* report, "In part, this problem has arisen because of disaggregation of the national effort across multiple agencies. The agencies have neither an enforceable mandate to cooperate in a manner necessary to be successful nor a system that requires accountability of expenditures. The Committee on Environment and Natural Resources (CENR) of the National Science and Technology Council was designed to improve the coordination of both the USGCRP agencies and the budget crosscuts with OMB in presenting a national program. Unfortunately, the management framework has not had the expected effect. The desired 'virtual agency'[23] has been quite far from reality."[24] The task group emphasizes that an effective national global change program cannot exist as mostly a collection of largely autonomous agency programs. It is our strong view that taking the steps outlined in this letter report will result in Earth science research by NASA that will be of the highest caliber, capable of supporting the crucial environmental decisions that face our nation and the world.

[1]Charles Kennel et al., *Report of the Workshop on NASA Earth Science Enterprise Post-2002 Missions*, NASA Headquarters, Washington, D.C., November 12, 1998. Referred to as the Easton workshop report and frequently as the Kennel report, it is available online at http://www.earth.nasa.gov/visions/Easton/index.html.

[2]National Research Council, Space Studies Board, "On Climate Change Research Measurements from NPOESS," letter report to Dr. Ghassem Asrar, NASA, and Mr. Robert S. Winokur, NOAA, May 27, 1998. This letter report may also be viewed at http://www.nationalacademies.org/ssb/npoess.htm.

[3]National Research Council, Board on Sustainable Development, *Global Environmental Change: Research Pathways for the Next Decade*, prepublication copy, National Academy Press, Washington, D.C., 1998.

[4]Public Law 101-606, 1990. The text of this act is reproduced as Appendix A of the *Pathways* report. See footnote 4.

[5]Overall direction and executive oversight of the USGCRP are provided by the interagency Subcommittee on Global Change Research of the National Science and Technology Council's Committee on Environment and Natural Resources. Representatives to the USGCRP include the Departments of Agriculture, Commerce (the National Oceanic and Atmospheric Administration and National Institute of Standards and Technology), Defense, Energy, Health and Human Services (the National Institute for Environmental Health Sciences), Interior, Transportation, and State as well as the Environmental Protection Agency, the National Aeronautics and Space Administration, the National Science Foundation, the Smithsonian Institution, the intelligence community, the Office of Science and Technology Policy, and the Office of Management and Budget.

[6]See Appendix A, "The Proposed USGCRP Budget for FY99," in *Our Changing Planet: The FY 1999 U.S. Global Change Research Program*, U.S. Global Change Research Program Office, Washington, D.C., 1998.

[7]National Research Council, Board on Atmospheric Sciences and Climate, *The Atmospheric Sciences Entering the Twenty-First Century*, National Academy Press, Washington, D.C., 1998.

[8]The 1994 *EOS Science Strategy* can be viewed at http://eospso.gsfc.nasa.gov/sci_strategy/Contents.html. More recent EOS science publications can be found at http://eospso.gsfc.nasa.gov/eos_homepage/scipubs.html.

[9]NASA began work on a science plan in 1998. However, officials told the task group that completion of the plan was postponed because of the urgency to develop the post-2002 missions.

[10]United Nations Framework Convention on Climate Change, Jan. 20, 1999, Report of the Conference of the Parties on Its Fourth Session Held at Buenos Aires From 2 to 14 November 1998, Addendum, Decisions Adopted By The Conference Of The Parties, Decision 14/CP.4, Research and Systematic Observation, p. 56. Available at http://cop4.unfccc.de/ or as Appendix E in National Research Council, Board on Atmospheric Sciences and Climate, *Adequacy of Climate Observing Systems*, National Academy Press, Washington, D.C., 1999.

[11]For a detailed examination of the role of R&A in NASA programs, see National Research Council, Space Studies Board, *Supporting Research and Data Analysis in NASA's Science Programs*, National Academy Press, Washington, D.C., 1998.

[12]Letter from Mr. Daniel Goldin, Administrator of NASA, to Dr. Neal Lane, Director, White House Office of Science and Technology Policy, February 1, 1999.

[13]The ESE was formerly known as the Mission to Planet Earth (MTPE). The program is managed by NASA's Office of Earth Science. Further information on the ESE is available at http://www.earth.nasa.gov/.

[14]Research Division, NASA Office of Earth Science, *ESE Mission Scenario for the 2002-2010 Period*, ver. 2.1, Oct. 5, 1998, p. 3.

[15]National Research Council and European Science Foundation, *U.S.-European Collaboration in Space Science*, National Academy Press, Washington, D.C., 1998.

[16]A similar view is expressed in the NRC report *Adequacy of Climate Observing Systems*, where it is stated that "there has been a lack of progress by the federal agencies responsible for climate observing systems, individually and collectively, toward developing and maintaining a credible integrated climate observing system." National Research Council, Board on Atmospheric Sciences and Climate, *Adequacy of Climate Observing Systems*, National Academy Press, Washington, D.C., 1999, p. 5.

[17]The report goes on to say that "for the measurements explicitly accepted as within the NPOESS mandate, there is no assurance that the quality of measurements, including accuracy, calibration, ground validation, and orbital parameters will be able to meet the scientific requirements [and] there are many other measurements of importance that NPOESS has no mandate to make."

[18]Letter from Mr. Daniel Goldin; see footnote 12.

[19]National Research Council, Board on Sustainable Development, *A Review of the U.S. Global Change Research Program and NASA's Mission to Planet Earth/Earth Observing System*, National Academy Press, Washington, D.C, 1995.

[20]HAPEX-Sahel (Hydrological and Atmospheric Pilot Experiment in the Sahel) is an international land-surface-atmosphere observation program that was undertaken in western Niger, in the West African Sahel region. The overall aims were to improve understanding of the role of the Sahel on the general circulation, in particular the effects of the large interannual fluctuations of land surface conditions in this region and, in turn, to develop ideas about how the general circulation is related to the persistent droughts that have affected the Sahel during the last 25 years.

The Boreal Ecosystem Atmosphere Study (BOREAS) is an international, interdisciplinary project that aims to determine the role of the boreal forest in the global climate system.
The Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) is an international research initiative led by Brazil that is studying the climatological, ecological, biogeochemical, and hydrological functioning of Amazonia, the impact of land use change on these functions, and the interactions between Amazonia and the Earth system. Information on these and related field experiments is available at http://www.inform.umd.edu/Geography/landcover/bvs/otherbvs.htm.

[21]Discussed in *Supporting Research and Data Analysis in NASA's Science Programs*; see footnote 11.

[22]National Research Council, Space Studies Board, "On Climate Change Research Measurements from NPOESS," letter report to Dr. Ghassem Asrar, NASA, and Mr. Robert S. Winokur, NOAA, May 27, 1998.

[23]"Virtual Agency" refers to the USGCRP interagency body. See p. ii in *Our Changing Planet: The FY 1998 U.S. Global Change Research Program*, U.S. Global Change Research Program Office, Washington, D.C., 1997.

[24]Overview volume of *Pathways* report, p. 14.

Appendix A

Task Group to Review NASA's Plans for Post-2002 Earth Observing Missions

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Appendix B

Request for Study

December 30, 1998

SPACE STUDIES BOARD
BOARD ON ATMOSPHERIC SCIENCES AND CLIMATE
BOARD ON SUSTAINABLE DEVELOPMENT

Assessment of NASA's Plans for Post-2002 Earth Observing Missions

SCOPE

This study will review NASA's planning for Earth observing missions during the period 2003 - 2010. Using existing relevant NRC reports, it will provide a top-level assessment of candidate mission scenarios in terms of their responsiveness to science priorities, disciplinary balance, and overall relevance to Earth system science. The study will be conducted collaboratively by appropriate units of the Policy Division, the Commission on Geosciences, Environment, and Resources, and the Commission on Physical Sciences, Mathematics, and Applications leading to a letter report to be delivered in the first quarter of 1999.

Earlier Work:
Earth Observations from Space: History, Promise, and Reality (SSB, 1995)
Letter report, "On Climate Change Research Measurements from NPOESS" (SSB, 1998)
Adequacy of Climate Observing Systems (BASC, 1999)
Overview, Global Environmental Change: Research Pathways for the Next Decade (BSD, 1998)
The Atmospheric Sciences Entering the Twenty-First Century (BASC, 1998)
The Role of Small Satellites in NASA and NOAA Earth Observing Missions (SSB, 1999 [in preparation])

CONTEXT

Policy Context:

As originally conceived in the 1980s, NASA's Earth Observing System (EOS) was to be flown on a series of large, multi-instrument orbital platforms. Subsequently in response, in part, to Congressional direction and a number of NRC reviews NASA has restructured the program. Current plans call for a suite of smaller spacecraft, each carrying a limited number of research instruments. The program also initially was intended to address a broad range of scientific issues in the Earth sciences, but the restructuring activities have moved the program toward a more focused set of objectives. NASA is now replanning the program to identify a set of missions to be flown in the period 2003 - 2010 after the first EOS platforms are launched. This replanning has involved solicitation of follow-on mission concepts from the scientific community and subsequent winnowing of these ideas into a "candidate mission scenario." The process used by NASA warrants review to determine how fairly and effectively it worked to recruit input from the broadest and most competent community of researchers.

NASA seeks an NRC review of the scenario to assist the agency in its FY2001 budget planning and international discussions about potential collaboration and coordination with space agencies abroad.

Technical Context:

The candidate mission scenario for Earth observing missions in the 2003 - 2010 time frame will need to be evaluated from a number of scientific and technical perspectives. First, there is the question of how well the planned mission set will address scientific questions of highest priority as outlined in recent NRC science strategy reports. Second, there is a need to look at scientific balance in terms of how well the planned mission set will address important scientific questions across a range of relevant disciplines in the Earth system sciences. There is also a need for a top-level assessment of the likely feasibility of the planned program in terms of technological readiness and ability of the proposed missions to meet basic requirements for data timeliness, continuity, and quality. NASA needs to be able to utilize such an assessment to plan for advanced technology development activities in support of the program and to formulate plans for an invitation for proposals for participation in the post-2000 missions in late 1999.

PLAN OF ACTION

Statement of Task:

An ad hoc task group composed of representatives from the BSD Committee on Global Change Research, the BASC Climate Research Committee, and the SSB Committee on Earth Studies, plus several additional experts, will conduct an assessment of NASA's proposed mission scenario for Earth observing missions in the period 2003 - 2010. Topics to be considered will include the following:

- the extent to which the mission set contributes to a coherent overall program that addresses important science themes and priorities,
- the responsiveness of the missions to scientific priorities identified in recent relevant NRC reports,
- broad aspects of balance between various Earth science discipline areas,
- general technical and programmatic feasibility,
- identification of major scientific or technical problems implicit in the mission scenario, and
- evaluation of the efficacy of the process employed by NASA to solicit ideas and to distill them to frame the proposed mission set.

NASA will provide summaries of the missions in the proposed mission scenario and a report on its August 1998 mission planning workshop for use in the review.

Consideration of Balance:
An ad hoc task group of approximately 12 members will be formed with the members drawn primarily from the membership of the SSB Committee on Earth Studies, the BASC Climate Research Committee, and the BSD Committee on Global Change Research.

Preliminary Work Plan:
The task group will utilize materials to be provided by NASA on the proposed post-2000 mission scenario. The task group will meet during the first quarter of 1999 for fact-finding and to develop its conclusions and recommendations and to outline a letter report. A 20-page report is planned for delivery no later than March, 1999, as requested by NASA.

Appendix C

EARTH SCIENCE ENTERPRISE
MISSION SCENARIO FOR THE POST-2002 PERIOD
Version 2.1

Research Division
Office of Earth Science
NASA Headquarters
October 10, 1998

ESE MISSION SCENARIO FOR THE 2002-2010 PERIOD

INTRODUCTION

The strategic goal of the Earth Science Enterprise is to expand scientific knowledge of the earth system using the unique vantage point of space. To achieve this goal, the Enterprise recognizes that scientific progress results from a multiplicity of converging approaches. While the pursuit of Earth System Science would be impossible without the global coverage provided by space-based instruments, integrating knowledge from in situ and space observations is equally essential. For this reason, NASA in cooperation with other science-funding agencies supports a balanced program of investigations based on satellite, airborne and surface measurements, as well as modeling and theoretical studies. This research strategy will be presented in a comprehensive, inter-disciplinary Research Implementation Plan under preparation by the ESE.

Notwithstanding this on-going effort, there was immediate need to plan future flight missions, in order to guide technology investments and identify prospective commercial and international partners. The purpose of the Request for Information (RFI) issued by the Enterprise was to explore planning options for future ESE flight missions during the period 2002-2010, following the completion of the first EOS series, and to construct a nominal mission scenario based on responses received to the RFI. The scenario reflects the scientific priorities formulated by national institutions (National Academy of Science/National Research Council) and international scientific bodies, and takes into account technical feasibility, estimated mission costs, and projected funding levels. The Earth Science Enterprise intends to periodically refresh this planning process through similar consultations of the Earth system science and applications communities at appropriate intervals in the future.

NASA informed RFI respondents of its intent to promote a program of smaller satellite missions, with a shorter implementation cycle, from inception to launch, in order to allow faster response to new research priorities and reduce the risk to overall program objectives from any single mission failure. *Smaller missions imply more focused mission objectives*, as recommended explicitly in the "Research Pathways" report of the Committee on Global Change Research of the National Academy of Science. This strategy, based on smaller satellite missions focused on narrower and more coherent science objectives, does not imply a retreat from the goal of the U.S. Global Change Research Program to embrace the full range of disciplines in Earth science and understand the behavior of the Earth as a system. It is envisioned that comprehensive Earth system models will provide the means to realize the necessary inter-disciplinary synthesis and integrate data from multiple sources, space-borne remote sensing and in situ measurements.

THE REQUEST FOR INFORMATION PROCESS

The purpose of the RFI process was to seek new ideas for space-based investigations and measurement concepts, to further develop the observation program initiated with the first series of EOS missions and take advantage of progress in instrument, spacecraft and information technology to pursue scientific advances and new applications within a lower cost profile. The RFI stated that the primary criterion for assessing the priority of new missions would be the significance of their scientific objective beyond the anticipated results of the first EOS series, and the maturity of required technologies. One hundred responses were received.

Step 1 of the RFI process consisted in scientific reviews of these responses by six panels covering complementary domains of earth system science and applications:

Atmospheric Chemistry

Atmospheric Climate Physics

Global Water Cycle, Hydrology and Mesoscale Weather

Ocean and Ice

Land Cover, Land Use and Terrestrial Ecosystems

Geodynamics and Geology

A survey of emerging science priorities in each disciplinary panel led to highlighting 23 mission concepts that were recommended for further technical and cost assessments. The mission concepts are described in a white Briefing Book, together with a summary of science priorities identified by the Step 1 review panels. Twenty-two missions concepts were actually analyzed by NASA technical staff and an industrial contractor. (One mission concept - Earth magnetic field monitoring - could be implemented through NASA participation in satellite missions of opportunity led by international partners.)

Step 2 of the RFI process begun with estimating Implementation costs, using a standard "cost model" developed by industry and based on the experience of past satellite missions. Instrument development costs were for the main part evaluated on the basis of information provided by RFI respondents, taking into account expected technology advances. Finally, the mission concepts were consolidated into a nominal "mission scenario" for the period 2002-2010, taking into account mission cost estimates and programmatic prospects for the Earth Science Enterprise. The nominal mission scenario and underlying programmatic guidelines were presented to a Post-2002 Mission Planning Workshop, held in Easton, MD (24-26 August 1998). The purpose of the Workshop was to allow discussion of the nominal scenario by a representative group of RFI respondents and an Interdisciplinary Review Panel of independent scientific experts. Specifically, the Workshop was asked to respond to three overarching questions:

Is the nominal mission scenario consistent with the **key scientific questions formulated by national and international bodies** representing the Earth System Science community?

Is the **balance between scientific disciplines** reflected in the nominal mission scenario consistent with emerging frontiers in Earth System Science?

Does the balance between **systematic measurement and discovery or process research missions** reflect an effective strategy to address key science questions in Earth System Science?

The report of the Workshop's Interdisciplinary Review Panel completed the RFI process. The ESE has requested that the National Academy of Science assess the resulting mission scenario, as amended as a result of the Step 2 Workshop.

THREE CATEGORIES OF MISSIONS

Different implementation procedures and constraints may apply according to mission objectives. For clarity, three categories of missions were distinguished:

EOS follow-on missions for systematic measurement of key earth system parameters.

Earth Probe missions for exploratory research or focused process-studies.

Pre-operational instrument development to provide new or more capable sensors for operational observing systems.

The three components of the program are briefly described below. In addition, the Enterprise is planning a University Earth System Science program (UnESS) of mini-missions, principally to serve educational objectives, capture the interest of the next generation of earth scientists and engineers, and encourage their participation in space remote sensing projects.

1. Systematic Measurement Missions

The first objective of NASA Earth Science Enterprise is to fulfill its commitment to the science community to maintain continuity of key EOS measurements, and deliver consistent time series of global observations over the period of time required by the nature of the earth system. The nominal plan of ESE is to meet this commitment within a sustained level of funding about 30% lower than comparable elements in the first EOS series.

In order to achieve this goal, NASA (1) proceeded to identify essential parameters requiring systematic measurement *from an earth system science perspective* and (2) promoted convergence of its global observation program with the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program. Appropriate bridging missions are identified in the nominal scenario to ensure measurement continuity in the interim period until operational observing systems deliver the required information. In addition, NASA will implement, to the extent possible, cooperation with private sector and international partners to implement joint projects that can provide research-quality global observations. Finally, the nominal plan calls for evolution toward smaller missions, each carrying a much simpler payload designed to provide a coherent set of measurements focused on a well-defined set of science themes.

2. Discovery and Process-research Missions

Based on estimated experimental mission costs, the nominal scenario allowed a multi-disciplinary Earth Probe program (incorporating Earth System Science Pathfinder missions) consisting of one discovery or process-research mission every nine months, beginning in 2004. Each mission is expected to provide a coherent set of measurements focused on a primary science theme. The Enterprise did not commit to a set program of experimental satellite missions for the next ten years. The intent is to issue successive solicitations for comprehensive mission implementation proposals addressing specific science themes selected by the agency. NASA will determine step by step the sequence of scientific disciplines addressed by the Earth Probe program, taking into consideration scientific priorities confirmed by scientific institutions and bodies, technical and funding capabilities, and opportunities for international cooperation.

3. Pre-Operational Instrument Developments

Implicit in the planning strategy for systematic global observation outlined above is the assumption that NASA will invest sufficient effort in technology and advanced operational instrument development to enable operational Earth observation programs, such as NPOESS and GOES, to provide research-quality measurements. The procedure to achieve the desired convergence and establish effective arrangements for joint participation in the development of these prototype operational sensors is being worked at the present time. NASA indicated readiness to invest in the development and/or flight demonstration of advanced observing capabilities that meet operational needs as well as long-term earth science objectives, when such projects are supported by a commitment of responsible operational agencies to participate in the development of the new sensors and implement their transition to operational use. The ESE would insert such pre-operational instrument developments into its flight mission program by re-ordering mission priorities in the systematic measurement, discovery or technology demonstration components (New Millennium Program) of the nominal mission scenario, as appropriate.

APPENDIX 1

SYSTEMATIC MEASUREMENT (EOS FOLLOW-ON MISSIONS)

Earth system science is dealing with a very complex dynamical system, governed by non-linear relations that can spontaneously generate variations of many time and space scales, from turbulent eddies to long-term changes in global ocean circulation. In addition, the system is subjected to a number of external forcing factors or changing boundary conditions. For lack of a capability to model and predict such external parameters (that may be controlled by inadequately known processes like solar activity, or changed by human actions), the only possible scientific strategy is the systematic observation of forcing and response, with the ultimate objective of linking one to the other. This is the fundamental reason why systematic observation and "climatological" data records play such an important role in this field of natural sciences.

The following represents a nominal mission plan for systematic measurement of atmospheric, oceanic and land variables to which Step 1 reviewers gave highest scientific priority *from an earth system science perspective*. The sequence of missions is ordered according to expected launch dates.

EOS-1: Land Cover/ Land Use Inventory Program

The Land Cover and Terrestrial Ecosystem research program calls for systematic measurement of changes in global land surface cover and land use, and estimation of their impact on the global carbon cycle, to be provided by a series of land imaging missions following Landsat-7. The same information is also essential for a wide range of value-added applications, such as forest and range management or agriculture. Each mission would carry one main instrument: multi-spectral (visible/near IR) imaging radiometer providing global coverage with sufficient spatial resolution (~10-20m) to unambiguously identify the extent of different type of vegetation or other land cover, and sufficient frequency (revisit time of the order of 15 days) to determine seasonal & long-term changes in terrestrial biomass. The instrument concept could be based on the Advanced Land Imager design being tested on the New Millennium EO-1 demonstration mission, with the addition of appropriate coarse-resolution spectral channels for atmospheric corrections. Progress in detector array technology, especially performance at non-cryogenic temperature, and high data-rate on-board processing are the main technology drivers for further optimization.

Implementation of the **first mission** in the series would begin in FY'01 for launch in year 2005, six year after the launch of Landsat-7. NASA intends to carefully examine private sector initiatives in this domain as a means for acquiring the relevant scientific data sets through data purchase instead of building a dedicated mission.

EOS-2: Climate Variability and Trend Mission

Most of what we currently know (or can infer) about the general circulation of the atmosphere and the global energy and water cycles is inferred from observation of basic meteorological variables, atmospheric pressure, temperature, moisture and wind. This information is obtained from a multiplicity of sources, in situ measurements by balloon-borne radiosondes at some 800 stations around the world and global remote sensing by atmospheric sounders on meteorological satellites. Currently, temperature and moisture profile data obtained from operational sounders suffer from significant weaknesses that make them less than ideally useful for atmospheric circulation analysis and forecasting (a large fraction of operational satellite sounder data is actually rejected by the more advanced data assimilation models). A decisive breakthrough is expected with the Advanced Infra-Red Sounder (AIRS), which is the first satellite sensor that can emulate the temperature and moisture measurement accuracy of radiosondes. It is expected that AIRS data will be available for the expected six-year lifetime of the PM-1 mission.

NASA is working closely with the NPOESS Integrated Program Office to enable similar temperature and moisture profile accuracy with the next-generation operational atmospheric sounder system that will be deployed on future operational environmental satellites. The objective of the *Climate Variability and Trend Mission*, given high priority by atmospheric climate research, is to continue research-quality temperature and water vapor measurements during the interim period between the termination of PM-1 and the first NPOESS flight. A single **bridging mission** is needed to fill the gap between EOS PM-1 and the first NPOESS satellite. In order to ensure measurement continuity, the mission would need to be launched no later than 2006, i. e. about six years after the launch of PM-1. NASA has selected several R. an D. projects under its Instrument Incubator Program (IIP) to develop the advanced technologies that can be applied to this mission.

EOS-3: Global Terrestrial and Oceanic Productivity Mission

The second highest scientific priority for Land Cover and Terrestrial Ecosystem research is systematic global observation of biological productivity at 1-2 day intervals at the best achievable spatial resolution (250-1000 m). Likewise, the oceanographic community gives high scientific priority to systematic observation of changes in ocean color and inferred ocean primary productivity. Moderate resolution global image data are also essential for a broad range of applications supported by NOAA, from smoke cloud detection to fisheries.

NASA's nominal plan in this domain is to promote the convergence of research and operational observation programs and eventually rely on NPOESS and other global operational observing systems in the future. A single **bridging mission** is needed to continue acquiring moderate-resolution multispectral imaging radiometer data from a morning orbit during the interval between the AM-1 mission and the first NPOESS flight. The nominal plan to fill this data gap would take advantage of the "Advanced Global Imager" (AGI) instrument currently under study jointly by NASA and the NPOESS program. For measurement continuity, the bridging mission would need to be launched no later than 2005, i. e. about six years after the launch of AM-1.

The Workshop agreed that the nominal plan, based on the use of the AGI instrument, could provide adequate baseline measurements but questioned the feasibility of obtaining research-quality data (especially ocean color measurements) from the NPOESS early morning and afternoon orbits. NASA agreed to study the impact of AGI design trade-off and NPOESS orbits from the perspective of marine ecosystem research and consider alternative means to acquire research-quality ocean color data.

EOS-4: Total Solar Irradiance Monitoring Program

The source of the energy that drives all climate processes is radiation from the Sun, known as the "solar constant" or, since we know now that the Sun is a (mildly) variable star, Total Solar Irradiance. NASA and other space agencies have maintained an essentially continuous record of total solar irradiance variations since 1979. NASA has undertaken the development of the next-generation total solar irradiance monitor (TSIM), to be flown in 2001 on a scientific satellite mission of opportunity built by Canada (SciSat). The plan is to eventually rely on measurements planned by the NPOESS program, beginning at the end of the decade. NASA made sure that the specifications of TSIM meet NPOESS requirements for solar irradiance monitoring.

In order to maintain the integrity of the total solar irradiance record, it is essential that successive TSIM missions provide sufficient overlap, since the stability (relative accuracy) of individual spaceborne radiometers is at least one order of magnitude better that their absolute calibration, and systematic differences between one instrument and the next can be as large as or larger than the signal. It is expected that one **solar irradiance monitoring mission** will be needed to ensure measurement continuity in the second half of the next decade (launch in 2005). The mission could be implemented on a small free-flying platform or as an instrument on space flights of opportunity. In addition, NASA is planning an intercomparison program of flight instruments with a laboratory-calibrated reference radiometer embarked on the Space Shuttle.

EOS-5: Ocean Surface Wind Measurement Program

The acquisition of surface wind data, interrupted in 1997 as a result of the premature shut-down of the NASDA/ADEOS satellite, will be resumed in late 1998 with the launching of the "QuickSCAT" recovery mission (using the first flight model of the new-generation Seawinds sensor developed by NASA), to be followed by the ADEOS-2 mission carrying the same Seawinds instrument in the year 2000 time frame.

The nominal NASA strategy for surface wind data acquisition in the long term is to rely on global measurements provided by two operational observing systems:

Passive dual-polarization microwave radiometer on the NPOESS satellite series during the next decade of the next century.

ASCAT active microwave scatterometer on the European METOP satellite series under development by EUMETSAT, with first launch planned in 2003.

The Workshop highlighted the importance of ocean surface (vector) wind data and insisted on the importance of full global coverage (which cannot be provided by a single ASCAT system) in order to capture fast weather developments and intense storms which contribute a disproportionate amount to mean oceanic forcing. NASA agreed to study the impact of data gaps in the coverage by a single scatterometer system. In addition to Europe's operational meteorological satellite program, the private sector also expressed interest in developing a constellation of small satellites equipped with scatterometers to provide global vector wind data. NASA plans to examine both operational agencies (NPOESS and EUMETSAT) and private sector plans prior to deciding on the development of a dedicated mission beyond Seawinds-1 on the Japan's ADEOS-2 mission. NASA also received informal indication of Japan's interest in flying a Seawinds-class instrument on the ADEOS-3 mission.

EOS-6: Ocean Surface Topography Mission

At the present stage of development, the highest priority for global oceanography is the continuity of essential dynamical measurements: ocean surface topography and ocean surface wind. NASA and the French space agency CNES cooperated to implement the very successful TOPEX/Poseidon ocean altimetry mission launched in 1992 and still operating nominally after six years. The US/French Jason-1 mission (to be launched in year 2000) will continue this key oceanographic measurement at the same or even better level of accuracy.

The nominal NASA strategy for global ocean topography observation is to rely on radar altimeter measurements from operational polar-orbiting satellites. Achieving the required (centimetric) accuracy from low-altitude sun-synchronous polar orbit, combining measurements from several platforms for appropriate temporal/spatial sampling, and correcting for solar tidal effects still poses scientific and technical problems. It is expected that these feasibility issues will be resolved by the Geosat and Jason-1 missions. Plans to proceed with the implementation of this measurement on NPOESS are being developed.

The Workshop concurred with the conclusion of the Step 1 reviewers that continuity of global ocean topography measurements has first priority for ocean circulation studies and climate research. The Workshop was concerned by the likelihood that a large data gap would occur between the Jason-1 ocean altimetry mission and the first NPOESS mission carrying a radar altimeter (early morning NPOESS spacecraft only), currently scheduled for 2011. Furthermore, the Workshop questioned the feasibility of achieving scientifically adequate precision and space-time sampling with altimetric measurements from low-altitude polar platforms. NASA agreed to investigate further the scientific and technical problems involved in ocean altimetry from polar spacecraft, and to consider the means to ensure the continuity of research-quality ocean topography measurements. In addition, NASA selected several R. an D. projects under the Instrument Incubator Program to develop the advanced technologies applicable to this mission.

EOS-7: Stratospheric Composition Measurement Program

The foremost scientific problem in the field of atmospheric chemistry remains the stabilization and eventual recovery of the stratospheric ozone layer. (Is the Montreal Protocol working as expected? Could other factors not yet recognized impair the recovery?). Considering that stratospheric chemistry is a relatively mature field, first priority for the discipline is given to monitoring the ozone distribution as a function of halogen concentration, trace gases and aerosols in the stratosphere. The measurement strategy assumes that future operational systems, in particular NPOESS, will provide research-quality total ozone data similar to Total Ozone Mapping Spectrometer (TOMS) observations. NASA will consider, with national and international partners, the means to ensure the continuity of global total ozone measurements in the interim period between the end of the EOS-CHEM mission and the first flight of the NPOESS series.

On this basis, the long-term systematic stratospheric composition measurement program could focus on accurate (essentially self-calibrating) observation of a relatively limited selection of precursor and reservoir species, at the minimum sampling rate that allows reliable detection of trends. Measurement methods of choice are occultation radiometry or spectrometry, and atmospheric limb emission radiometry. In order to achieve adequate geographic coverage, the mission requires a 2-spacecraft constellation, one in sun-synchronous orbit and the other on an inclined (50-60°) orbit.

Implementation of the sun-synchronous component could begin in FY'04 for launch of the first spacecraft of the series in late 2008, six year after EOS-CHEM. The nominal option for implementation of the inclined-orbit component is a succession of attached payloads on the International Space Station (ISS). Fabrication of instruments for the attached payloads could be completed in a 2-3 year period beginning in FY'02 or 03.

EOS-8. Topography and Surface Change Mission

Land surface topography is a fundamental geophysical parameter that influences the interaction between the atmosphere, hydrosphere and solid earth, and a key observable for assessing natural hazards such as floods, coastal storm surges, landslides, etc. Changes in topography provide information on crustal strain that is essential to understand the physics of solid earth and may provide precursor signal to impending natural hazards such as earthquakes and volcanic eruptions. Detailed topography of the polar ice sheets also yields critical information on ice flow dynamics and, indirectly, the changing mass balance of the ice sheets.

The solid earth and polar science community place high scientific value on repeat synthetic aperture radar (SAR) mapping of land surface and ice, and specifically the implementation of a tandem SAR mission that would allow the best possible interferometric reconstruction of global topography (comparable in principle to, but more precise than, the Shuttle Radar Topographic Mission in 1999). Emerging applications in the domain natural hazard reduction provide a strong incentive to maintain nearly continuous SAR coverage of the earth through the next decade. Significant periods of overlap between successive missions would allow implementing bistatic radar interferometry.

NASA intends to carefully examine private sector investments in the field of global SAR observation, beyond its first free-flying SAR mission planned in the early 2000 time frame, and plans to acquire the needed scientific data through data purchase whenever possible. Cooperation with international partners is also an open possibility to ensure observation continuity.

EOS-9: Global Precipitation Mission

The scientific focus of global water cycle research and hydrologic sciences is understanding and predicting the impact of climate change on weather events, river flow and water resources. The discipline recognized that global rainfall distribution is the foremost measurement required to progress toward quantitative knowledge of the water cycle and arguably the most accessible hydrologic quantity for satellite remote sensing. Among several possible techniques, passive and active (radar) microwave measurements from low earth orbit is the most mature and reliable approach.

Precipitation is associated with mesoscale weather systems that display considerable spatial and temporal variability. For this reason, high sampling frequency is essential: a sampling interval of three hours or less is required to estimate total rainfall reliably. Measuring rainfall from space would requires a constellation of at least 4 spacecraft in staged polar orbits. The nominal concept is to fly only one "master" rainfall-measuring satellite carrying both active (Precipitation Radar) and passive (Microwave Radiometer/Imager) sensors, and a number of "drone" satellites carrying only the passive microwave sensor. Considering that two DMSP spacecraft equipped with the SSM/I microwave radiometer are expected to be in operation, two drones would be sufficient to complete the constellation. The master satellite mission could be implemented on a dedicated platform, while the drones would be smaller free-flying spacecraft. The nominal plan was to begin implementation in FY'04, aiming for launch in year 2007 four years after the TRMM follow-on mission under consideration by NASDA.

The Workshop agreed that implementing the original objective of EOS to measure global precipitation had very high scientific value for the progress of earth system science. The Workshop further noted that the Japanese space agency's plan for a TRMM follow-on mission were not firm and recommended that the implementation of a global rainfall measuring mission be advanced to the 2003 time-frame. NASA agreed to carefully examine opportunities for an earlier implementation and explore possible international partnerships.

EOS-10: Polar Altimetry Mission

The central question of polar climate science is the detection of changes in ice sheet dynamics and mass balance. For this purpose, systematic precision measurements of Greenland and Antarctic ice sheet topography are needed at appropriate intervals. The first measurement will be provided by the Icesat mission (launch date: 2001) as part of the first EOS series. The nominal plan included a repeat mission around 2010, using either one of two possible techniques that may (precision lidar and synthetic-aperture radar altimeter).

The Workshop highlighted the importance of precision altimetry as the centerpiece of a systematic measurement strategy for ice-sheet dynamics and ice mass balance studies, and expressed concern about the expected discontinuity between the first Icesat mission and a repeat mission launched near the end of the next decade. NASA agreed to assess the scientific impact of a discrete (discontinuous) sampling strategy for the study of ice sheet dynamics.

APPENDIX 2

EXPLORATORY AND PROCESS RESEARCH-ORIENTED MISSIONS

Progress toward more a fundamental understanding of the earth system, based on first physical, chemical or biological principles, will primarily result from process-oriented research or discovery missions. Such missions will need to collect adequate but not necessarily complete global data sets that sample the full global range seasonal and geographic conditions for periods of (typically) 3 to 5 years. Such research missions can be taken as the discovery component of the ESE flight program. They respond to the recommendation of the National Academy of Science/National Research Council to promote an innovative program of focused research satellite projects addressing sharply defined science questions.

Exploratory missions may entail high scientific and technical risks, as investigators try to break into new fields of investigation, and attack unsolved scientific questions with the resources of the latest technology. It would be unwise at any time to define a ten-year program of experimental missions that would ignore future prospects for new scientific ideas, new technological advances and unforeseen science breakthroughs. In this regard, it is best to select each new experimental mission through a solicitation process open to a range of competing projects as late as possible in the implementation process, following a practice pioneered in the Earth System Science Pathfinder program.

On the other hand, it is essential to correctly gauge the scope of the exploratory mission program that would optimally balance the systematic measurement component in the overall research strategy for the Enterprise. For this purpose, NASA applied the same scientific evaluation, technical feasibility and cost assessment procedures to both systematic measurement and discovery mission concepts. The candidate mission concepts described below are those that emerged as particularly promising in the Step 1 review. This set should be considered as illustrative of the discovery missions that might be implemented in response to scientific priorities that will emerge in the next ten years, and does not suggest a particular implementation order. Several among these mission concepts have already been considered by partner agencies abroad and would therefore be good candidates for joint cooperative projects.

Each of candidate experimental mission listed below has been highlighted by Step 1 reviewers as essential for the advancement of their respective scientific disciplines and is representative of the state of the art. However, this set of mission concepts by no means represents the variety of meritorious ideas that were presented in the RFI process, nor the diversity of new proposals that may emerge in the future from regular Announcements of Opportunity or the next program-wide RFI. The ordering of the candidate missions *does not reflect a judgment of scientific priority*, and the actual Earth Probe mission program of the Enterprise remains to be determined by successive solicitations and a competitive selection process.

EX-1: Tropospheric Chemistry Research Mission(s)

Tropospheric chemistry is generally taken as the next frontier of global atmospheric chemistry. While ozone is a relatively minor constituent of the troposphere, ozone is specially important in tropospheric chemical processes as it reflects the oxidizing power (and cleansing effect) of the troposphere. Another essential research topic is the long-range transport and diffusion of pollutants from surface sources, and the global atmospheric impacts of large-scale pollution from emerging industrial nations.

Observation of chemical/dynamical processes in the troposphere faces two challenges: the need for sufficient vertical resolution to identify the layered structure of constituents transported by the atmospheric circulation and the need for adequate temporal resolution to resolve possible diurnal variations and fast emission events. The latter requirement would be ideally fulfilled by observation from geostationary orbit, except for the fact that feasible measurement are generally lacking in vertical resolution within the troposphere. Differential absorption lidar and other active sounding systems operating from low earth orbit can ideally meet the requirement for vertical resolution, but only provides relatively sparse sampling. The Step 1 review panel for Atmospheric Chemistry concluded that, given a choice between vertical resolution and high sampling frequency, the former had the highest potential for discovery. This scientific judgment is reflected by the scientific priority given to a number of promising measurement concepts in low earth orbit.

The scientific discovery potential of global tropospheric chemistry justifies **at least one and ideally two experimental missions** during the period of reference. Each would a one-time mission, carrying a payload limited to a small number of sensors (to be determined by the assessment of competing research mission proposals). The instrument payload could include passive and active sensors (such as tunable differential absorption lidars) to observe ozone, CO and precursor species, or pollutant emitted by surface sources (SO2, hydrocarbons, etc.).

EX-2: Aerosol Radiative Forcing Research Mission

A high visibility issue in climate change research is the impact of natural and anthropogenic aerosols on the radiative balance of the planet. One possible strategy for investigating this problem is based on monitoring trends in the global distribution of stratospheric and tropospheric aerosols. Two candidate systematic observation missions listed in Appendix 1 address this objective (measurements of solar occultation by stratospheric aerosol and solar radiation backscatter by tropospheric aerosol).

Nevertheless, the diversity of aerosol origin, composition and optical properties, and the complexity of radiation scattering and absorption by aerosol and ice/water particles are so overwhelming that conclusive findings can only be expected from considerably more sophisticated and penetrating observations. It is essential, in particular, to resolve the vertical layering of aerosol distribution in order to backtrack tropospheric transport and identify the source of the material. The instrument payload that could provide this information would be organized around a backscatter lidar with a range of smaller complementary sensors (polarimeter, multi-directional radiometer, etc.) that could contribute to characterizing the size, shape and optical properties of aerosol and (optically thin) cloud particles.

EX-3: Cloud-Radiation Feedback Research Mission

After water vapor, clouds are the next largest contributors to the planetary greenhouse effect (about 30 Watt/m^2). Altogether, the net radiative impact of clouds on the planetary radiation balance is large (of order of - 20 Watt/m^2) and highly variable. The cloud response to changing climatic conditions is the biggest source of uncertainty in climate model simulations, to say nothing of the essentially unknown indirect radiative forcing of aerosols through the modification of cloud particle size and optical properties. Understanding and modeling cloud processes with adequate accuracy remains the most vexing problem of climate physics, despite decades of research in cloud physics and progress toward explicitly introducing cloud micro-physical processes in specialized "cloud resolving models" and general circulation models. A principal reason is the lack of sufficient (global) observational data to reflect the diversity of weather phenomena and climatic regimes in which clouds are embedded. Understanding cloud-radiation feedback in the context of climate change is the frontier of atmospheric radiation research.

Effective observing tools to resolve the diversity of cloud system geometry and the complexity of cloud optical properties are only now becoming available: backscatter lidar, cloud profiling radar operating in the millimeter wave range, precipitating cloud profiling radar operating in the centimeter wave range, visible, IR and sub-millimeter radiometers or spectrometers. Considering the complexity of the problem and the diversity of observing tools that can shed light on some aspects of the problem, no single cloud-radiation research mission can be singled out as uniquely effective, but several candidate concepts appear thoughtful and scientifically promising.

Any such mission would be organized around a cloud profiling radar and lidar system (the only observing technique that can provide adequate vertical resolution and detect overlapping cloud layers), with complementary passive sensors focused on the same atmospheric column. (The spatial variability of cloud is such that the benefit of multiple sensor observation would be compromised if co-registration was lost.) A **state-of-the-art cloud-radiation feedback research mission** would be a relatively ambitious project, requiring a medium-size spacecraft and a multiple instrument payload (to be determined by selection of one among several comprehensive proposals for mission concept and implementation). This particular experimental mission concept has been studied in depth by at least two partner agencies and would therefore be a good candidate for a joint international cooperative project.

EX-4: Soil Moisture and Ocean Salinity Observing Mission

Soil moisture, a component of ground water storage, is the state variable that represents the terrestrial hydrologic system on time scales relevant to flooding, evapotranspiration and impacts on vegetation (water stress). Soil moisture integrates precipitation and evaporation over periods of days to weeks and introduces a significant element of memory in the atmosphere/land system. There is strong climatological and modeling evidence that the fast recycling of water through evapotranspiration and precipitation is the primary factor in the persistence of dry or wet anomalies over large continental regions during summer. On this account, soil moisture is the most significant boundary condition that controls summer precipitation over the central US and other large mid-latitude continental regions, and essential initial information for seasonal predictions. Precise in situ measurements of soil moisture are available but each value is only representative of a small area.

Remote sensing, if achievable with sufficient accuracy and reliability, would provide truly meaningful wide-area soil wetness or soil moisture data for macroscale hydrological studies and precipitation anomaly prediction over large continental regions. The most mature technique, low-frequency passive microwave radiometry, would also allow the determination of Sea Surface Salinity (SSS). Global surface salinity measurement would provide invaluable information to close the planetary water budget over the oceans and understand the pre-conditioning of surface waters that controls deep water formation in the north Atlantic. The SSS measurement places a challenging requirement on the sensitivity (signal/noise ratio) of spaceborne passive microwave radiometers.

The measurement of soil moisture (and ocean salinity) must still be considered experimental and, for this reason only, was ranked as the second priority of the Hydrology and Global Water Cycle discipline. Developing an effective soil moisture remote sensing system based on passive radiometry requires the deployment of very large antennas (or realization of a correspondingly large synthetic aperture) in order to achieve meaningful spatial resolution (of order ~ 10 km or less) at the relatively low microwave frequencies that can penetrate moderately dense vegetation. The objective of an experimental **soil moisture/ocean surface salinity measurement mission** would be a 3 to 5 year demonstration of an advanced low-frequency dual-polarization passive microwave radiometer or combined active/passive system in low earth orbit (to be determined by selection of competing mission proposals).

EX-5: Time-Dependent Gravity Field Mapping Mission

Measuring the time-varying component of the gravity field is a totally new "remote sensing" approach that provides a unique insight in mass redistribution within the earth system, including climate effects such as ground or surface water storage, and changes in oceanic circulation, as well as tectonic motions and post-glacial rebound. The concept of measuring temporal variations in the gravity field to monitor mass redistribution has already been demonstrated, using various time series of geodetic and gravimetric data. The Earth System Science Pathfinder GRACE mission will extend this proven capability to harmonics above 100. There are strong expectations from both the solid earth science community and global oceanography community that the GRACE mission (to be launched in 2001) will be a pathfinder for a powerful new method to investigate geophysical and geodynamic phenomena.

If this breakthrough is achieved, further technological advances are clearly in sight that will allow at least one order of magnitude improvement in the sensitivity of the method, thus expanding the range of scientific applications. Knowledge of the geoid is a limit to the scientific utility of sea-surface topography data for dynamic oceanography at shorter length scales. Advanced satellite-to-satellite tracking in low Earth orbit would allow significant refinements of the shape of the geoid down to 50-100 km scales, comparable to the scale of ocean eddies and the exploitation of altimetric observations closer to continental margins to characterize coastal currents). In addition, directly detecting changes in total water column mass would allows computing the mean geostrophic flow or Sverdrup circulation.

In view of the fundamental importance of earth gravity data, the oceanic, polar and geodynamic disciplines would place this measurement in their top two or three scientific priorities for long-term systematic observation of fluid and solid earth. On the other hand, the required technology (satellite-to-satellite laser interferometry) is definitely a technical challenge, so that the concept must still be considered experimental. An **experimental mission** would involve launching two essentially identical spacecraft on the same orbit with a single launch vehicle. Operational life time should be a minimum of five years. In view of a broad international interest in space geodesy, this mission would be also a likely candidate for an international cooperative project.

EX-6: Vegetation Recovery Mission

Understanding the carbon cycle is essential to assess future changes in the atmospheric concentration and greenhouse effect of carbon dioxide. A major component of this cycle is net ecosystem productivity in terrestrial temperate and boreal ecosystems, which integrates the regrowth of previously disturbed landscapes, carbon dioxide fertilization, and the result of nitrogen deposition. Quantifying the first of these effects is critical to understanding the response of the carbon cycle to human perturbations.

For this reason, the land cover and terrestrial ecosystems discipline places high priority on a disturbance recovery mission, that could be flown in the late 2000's time frame. The main instrument would be a steerable lidar altimeter system, based on technological evolution of the ESSP Vegetation Canopy Lidar mission (to be launched in year 2000). The purpose of the mission would be to sample the evolution of specific terrestrial biosphere targets that have been subject to major disturbances, like clear-cutting or fires. The scientific objective is to characterize the recovery of above-ground biomass in those areas. A complementary visible-near IR imager could document the recovery of grasslands and semi-arid ecosystems. Altogether this **experimental mission** could be implemented on a small spacecraft and aim for a 3-5 year life time.

X-7: Cold Land Processes Research Mission

Over large regions (e. g. the interior of North America and Eurasia) and high altitude mountainous areas, much of the annual precipitation contributing to streamflow occurs in the form of snow during the winter months. Snow accumulation is a major storage term that strongly impacts the seasonal cycle of runoff. The freeze-thaw status of the soil surface determines the partitioning of precipitation or snowmelt between runoff and infiltration. The high albedo of snow-covered terrain results in large contrasts in net radiation during the thaw period. Important science questions that come to mind are:

How does the extent of snow and frozen ground affect atmospheric climate?

Can snow water equivalent be quantified from remote sensing data with sufficient accuracy to improve hydrologic forecast?

Could these factors be measured accurately enough to identify meaningful climatic trends?

Snow water equivalent and the extent of frozen ground have not been adequately measured from space, due to limitations in spatial resolution of passive microwave instruments and the poor sampling frequency achievable with existing spaceborne imaging radar systems. A promising, but technically challenging measurement concept is based on applying active SAR imaging techniques at relatively coarse spatial resolution (of order ~ 1 km) to detect freezing conditions on the ground, the extent & amount of snow, and probably various vegetation properties. Coarse resolution could allow a wider swath and short repeat cycle (~ 3 days). This **experimental mission** could be implemented on a dedicated platform in low altitude sun-synchronous orbit. The primary payload would be a 2-polarization, coarse resolution SAR system at L-band or lower frequency. The technical challenge is measuring the intensity of the backscatter signal with much higher accuracy than currently envisaged in high-resolution imaging radar systems.

NASA intends to carefully examine and take advantage of potential commercial and international initiatives in this domain of global SAR observation with high revisit frequency and relatively coarse spatial resolution.

APPENDIX 3

PROTOTYPE OPERATIONAL INSTRUMENT DEVELOPMENT

The Step 1 review highlighted several projects to develop and demonstrate new sensors intended for operational applications as particularly meaningful for scientific research. It has been long recognized that earth system science relies heavily on information and climatological records acquired and archived by operational environmental agencies (for a variety of applications). This is especially true in the field of climatology, as most of what is currently known about the earth climate is derived from the study of weather observation records. Thus, improving the capabilities of operational observing systems (especially polar satellites that provide global coverage) is also essential for the progress of earth system science.

On the other hand, there is currently no established process for identifying joint scientific and application priorities for operational sensor developments, nor for transition from scientific developments to the procurement and accommodation of new operational instruments on operational satellite systems. The development and flight demonstration of specific prototype operational instruments is not explicitly included in the nominal mission plan but could be accommodated by re-ordering flight priorities in the Enterprise's

EOS follow-on, Earth Probe and New Millennium programs. NASA is seeking active participation of cognizant user agencies in the definition, development and transition to operational use of new advanced instruments that would meet ESE long-term science objectives as well as operational application requirements. The following is a list (no priority order implied) of instrument concepts that were discussed in the RFI process or otherwise brought to the attention of the Enterprise:

The Workshop generally agreed with this new NASA approach to contributing to the development of new or improved operational observing capabilities. Although no discipline had ranked high-frequency observation from geostationary orbit as their highest scientific priority, there was general recognition of the value of developing a new geostationary sensors for a diversity of research and application objectives. NASA has focused the forthcoming announcement of opportunity for the next New Millennium Program technology demonstration mission precisely to address this objective. NASA is also holding consultations with NOAA/NESDIS on priorities for the development of improved sensors for operational GOES satellites.

OP-1: Advanced Microwave Sounder

The current operational microwave sounder suite, including AMSU-A and MHS, has a total mass of 160 kg. The utilization of new microwave circuit technology would permit substantial weight reduction for the same functionality and the addition or substitution of new microwave channels that would better support the retrieval of precision temperature/moisture soundings in combination with a companion IR sounder. NASA had studied the feasibility of upgrading existing microwave sounders, as part of the Integrated Multispectral Atmospheric Sounder (IMAS) project. Significant progress had been made in the development of microwave technology at the relevant (very high) frequencies and NASA plans to apply these technique to the development of an advanced operational microwave sounder for NPOESS.

OP-2: Tropospheric Wind Sounder

Global measurement of tropospheric wind has been widely heralded as potentially the most significant contribution of satellite remote sensing to existing global meteorological observations (World Weather Watch). Direct measurement of horizontal wind vectors in clear air has been demonstrated using lidar from the ground and from aircraft, based on determination of the wind-induced Doppler shift in the backscatter signal. Two competing techniques are envisaged:

> Coherent detection Doppler lidar system, which is the most sensitive and potentially most accurate technique, but works only in atmospheric layers where sufficient density of scattering particles exists (aerosols). The technique requires development of a unique laser transmitter technology.
>
> Incoherent detection Doppler lidar system, which is less sensitive but operates uniformly in clear air (works with both Mie scattering from aerosol particles and Rayleigh scattering from air molecules). The technique can utilize a widely used type of laser transmitter.

NASA is preparing a demonstration of the first technique (coherent detection) on a Space Shuttle flight in 2001 (SPARCLE project). There is also private sector interest in developing alternate measurement techniques which could offer the prospect of the availability of tropospheric wind data from a commercial provider.

OP-3: GPS Constellation for Atmospheric Sounding

Measurement of the phase-delay occurring in the propagation of GPS signals near the limb of the atmosphere allows inferring dry air density, temperature and pressure as a function of geopotential height in the region where the concentration of water molecules remains negligible. Below this level, the same technique allows estimating water vapor concentration, provided reasonably accurate temperature information can be obtained from other sources. Altogether, the technique is a completely different approach to atmospheric sounding and would, in principle, provide practically drift-free temperature information throughout the upper troposphere and lower stratosphere, as well as unmatched vertical resolution. Further refinements are also conceivable to extend the domain of application of this and related microwave limb sounding methods.

NASA has made substantial investments in the development of relevant spaceborne GPS receiver technology, as well as software for flight equipment operation and data processing. NASA has also begun to constitute an experimental GPS constellation by furnishing GPS equipment to scientific satellite missions of opportunity developed by international partners. It is expected that this international system will deliver a sufficient number of GPS soundings per day to carry out a meaningful test of the impact of this type of data on the quality of global weather forecast (although only in a delayed or "hindcast" mode).

A further initiative, co-sponsored by UCAR and the Taiwan Academy of Sciences would launch a constellation of 8 dedicated micro-satellites, allowing real-time collection of GPS measurements and delivery of temperature/moisture profile data to weather forecasting centers in time for insertion into the operational analysis and prediction system. NASA is considering possible means to demonstrate this new observing technique.

OP-4: Advanced Geostationary Sounder

One of the two principal sensor on NOAA Geostationary Operational Environmental Satellites (GOES) is an IR atmospheric sounder of relatively conservative design and technology. The sensor allows repeated soundings at very short time intervals over specific regions of interest (where rapid weather development is being observed). However the lack of vertical resolution in the lower and mid-troposphere, where rapid weather development actually occurs, reduces the usefulness of frequent soundings for the purpose of numerical weather prediction. This deficiency could be

overcome by a new sounder instrument using state-of-the-art technology (in particular, advanced IR detector arrays and mechanical cryogenic cooling systems). Dynamical meteorology supports the expectation that AIRS-grade temperature and moisture soundings at high spatial and temporal resolution would bring a significant improvement in the ability to forecast mesoscale weather systems and, in general, assist with severe storm warning.

OP-5: Volcanic Ash and Gas Emission Mapping Mission and Advanced Geostationary Earth Imager

The visible and IR imaging radiometer on the current GOES series is a new instrument design that delivers images of the earth disc with unprecedented spatial and temporal resolution. Nevertheless, several improvements are envisaged, such as augmenting the number of spectral channels and further increasing spatial resolution. These upgrades would be justified by a multiplicity of operational applications of geostationary imager data, from tornado warning to fire detection to tracking ash clouds from volcanic eruptions.

OP-6: Special Event Imager

The "Special Event Imager" concept (SEI) is a steerable high-resolution imager that could be pointed to stare at occasional or predictable regional events that vary within a time span of hours rather that days. The SEI is being promoted by the biological oceanography community as well as operational users as a desirable addition to the standard payload of GOES satellites. In addition to numerous applications from wildfire assessments to algal bloom monitoring, the SEI could provide invaluable ocean color change information to capture coastal phenomena that are dependent upon tidal effects.

OP-7: Geostationary Lightning Mapper

Electrical charges that cause lightning strikes are created by rapid ascending air flow associated with strong convective storms. There is evidence that instantaneous mapping of lightning strikes over the disc of the earth from geostationary orbit would enhance the ability to judge the strength of developing storm cells and forecast the likelihood of tornadoes and severe downdraft. The strike rate can also be related in a semi-quantitative manner to convective precipitation. Altogether, a geostationary lightning mapper holds considerable attraction for weather forecasters, but the scientific significance of such observations from one or two geostationary satellites does not match the scientific interest of global lightning distribution data obtained by the NASA-provided lightning detection sensor on TRMM.

NOTE: Reprinted from Charles Kennel et al., *Report of the Workshop on NASA Earth Science Enterprise Post-2002 Missions*, NASA Headquarters, Washington, D.C., November 12, 1998, Appendix 1. Available online at http://www.earth.nasa.gov/visions/Easton/index.html.

Appendix D

Task Group Meeting Agenda

WEDNESDAY, FEBRUARY 10, 1999

8:00 a.m.	Continental Breakfast	
	Closed Session	
8:30 a.m.	Discussion of task, initial views of the task group	M. Geller, *Chair*
	Bias and conflict discussion	Sherburne Abbott
	Open Session	
	(A.M. session meets jointly with the Committee on Earth Studies)	
9:30 a.m.	NASA presentations	G. Asrar and P. Morel
11:00 a.m.	NOAA and NPOESS IPO presentations	C. Nelson, Mike Crison, Ray Taylor
12:30 p.m.	Lunch and discussion of Pathways report[1]	B. Moore
1:30 p.m.	Review of Easton meeting	L. Shaffer
2:00 p.m.	Discussion with Sarah Horrigan	Office of Management and Budget
2:30 p.m.	Discussion with Bob Corell	National Science Foundation
3:00 p.m.	Discussion with Rosina Bierbaum	Office of Science and Technology Policy
3:30 p.m.	Break	
4:00 p.m.	Discussion of NPOESS integration report[2]	M. Abbott
4:30 p.m.	Discussion of 21st century report[3]	E. Barron
5:00 p.m.	Open session for roundtable or splinter discussions among task group members, presenters, and invited scientists	
6:00 p.m.	Adjourn for reception	

THURSDAY, FEBRUARY 11, 1999

8:00 a.m.	Continental Breakfast	
	Closed Session	

8:30 a.m.	Task group discussion and writing
5:30 p.m.	Adjourn

[1]National Research Council, Board on Sustainable Development, *Global Environmental Change: Research Pathways for the Next Decade*, prepublication copy, National Academy Press, Washington, D.C., 1998.

[2]National Research Council, Space Studies Board, "On Climate Change Research Measurements from NPOESS," letter report to Dr. Ghassem Asrar, NASA, and Mr. Robert S. Winokur, NOAA, May 27, 1998.

[3]National Research Council, Board on Atmospheric Sciences and Climate, The Atmospheric Sciences Entering the Twenty-First Century, National Academy Press, Washington, D.C., 1998.

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